Advanced Mirror Technology Development

(AMTD)

for Very Large Space Telescopes

Status: Year 2 of multi-year effort

H. Philip Stahl
Astrophysics Roadmap Team

6 May 13
Most future space telescope missions require mirror technology. Just as JWST’s architecture was driven by launch vehicle, future mission’s architectures (mono, segment or interferometric) will depend on future launch vehicle capacities (and also budget). Since we cannot predict future, we must prepare for all futures. UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

- Very Smooth Surfaces $< 10$ nm rms
- Thermal Stability Low CTE Material
- Mechanical Stability High Stiffness Mirror Substrates

Finally, Telescopes are only 15 to 25% of Total Mission Cost.
AMTD Approach

Mirror technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

Outstanding academic, industry & government team with expertise:
- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.

Integrate science & systems engineering to:
- derive engineering specifications from science measurement needs and implementation constraints;
- identify technical challenges in meeting these specifications;
- iterate between science and systems engineering to mitigate challenges; and
- prioritize the challenges.

Systematically mature TRL of prioritized challenges using
- design tools to construct analytical models and
- prototypes/test beds to validate models in relevant environments.
Objectives

Derive engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 6 inter-linked critical technologies.

- *Large-Aperture, Low Areal Density, High Stiffness Mirrors*: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.

- *Support System*: Large-aperture mirrors require large support systems to ensure that they survive launch and deploy on orbit in a stress-free and undistorted shape.

- *Mid/High Spatial Frequency Figure Error*: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.

- *Segment Edges*: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.

- *Segment-to-Segment Gap Phasing*: Segment phasing is critical for producing a high-quality temporally stable PSF.

Philosophy

Simultaneous technology maturation because all are required to make a primary mirror assembly (PMA); AND, it is the PMA’s on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.

We are deliberately pursuing multiple design paths to enable either a future monolithic or segmented space telescope

- Gives science community options
- Future mission architectures depend on future launch vehicles, AND
- We cannot predict future launch vehicle capacities
# AMTD Project Technical Team

## Principle Investigator

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<tbody>
<tr>
<td>Dr. H. Philip Stahl</td>
<td>MSFC</td>
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## Systems Engineering

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<tr>
<th>Name</th>
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<tr>
<td>Dr W. Scott Smith</td>
<td>MSFC</td>
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## Science Advisory

<table>
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<tr>
<th>Name</th>
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<tr>
<td>Dr. Marc Postman</td>
<td>STScI</td>
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<tr>
<td>Dr. Remi Soummer</td>
<td>STScI</td>
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<tr>
<td>Dr. Arund Sivaramakrishnan</td>
<td>STScI</td>
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<tr>
<td>Dr. Bruce A. Macintosh</td>
<td>LLNL</td>
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<tr>
<td>Dr. Olivier Guyon</td>
<td>UoAz</td>
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<td>Dr. John E. Krist</td>
<td>JPL</td>
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## Engineering

<table>
<thead>
<tr>
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<tr>
<td>Laura Abplanatp</td>
<td>Exelis</td>
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<td>Ron Eng</td>
<td>MSFC</td>
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<td>William Arnold</td>
<td>MSFC</td>
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## Integrated Modeling

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<tr>
<td>Gary Mosier</td>
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<td>William Arnold</td>
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<tr>
<td>Anis Husain</td>
<td>Ziva</td>
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<td>Jessica Gersh-Range</td>
<td>Cornel</td>
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## AMTD-2 Proposal

<table>
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<th>Name</th>
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<tr>
<td>Tony Hull</td>
<td>Schott</td>
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<tr>
<td>Andrew Clarkson</td>
<td>L3-Brashear</td>
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## Funding

- NASA ROSES SAT (10-SAT10-0048)
- Space Act Agreement (SAA8-1314052) with Ziva Corp
- NASA Graduate Student Research Program (NNX09AJ18H)
Heritage

AMTD builds on over 30 yrs of US Gov mirror technology development:
Goals, Progress & Accomplishments

Systems Engineering:
- derive from science requirements monolithic mirror specifications
- derive from science requirements segmented mirror specifications

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:
- make a subsection mirror via a process traceable to 500 mm deep mirrors

Support System:
- produce pre-Phase-A point designs for candidate primary mirror architectures;
- demonstrate specific actuation and vibration isolation mechanisms

Mid/High Spatial Frequency Figure Error:
- ‘null’ polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.

Segment Edges:
- demonstrate an achromatic edge apodization mask

Segment to Segment Gap Phasing:
- develop models for segmented primary mirror performance; and
- test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.

Integrated Model Validation:
- validate thermal model by testing the AMSD and deep core mirrors at 2°C; and
- validate mechanical models by static load test.
9 Publications from Year 1


Engineering Specifications

Derived engineering specifications for monolithic primary mirror from science measurement needs & implementation constraints.

Segmented mirror specifications are in-process.

Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions

<table>
<thead>
<tr>
<th>Science Question</th>
<th>Science Requirements</th>
<th>Measurements Needed</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is there life elsewhere in Galaxy?</td>
<td>Detect at least 10 Earth-like Planets in HZ with 95% confidence.</td>
<td>High contrast ($\Delta$Mag $&gt;$ 25 mag) SNR=10 broadband (R = 5) imaging with IWA $\sim$40 mas for $\sim$100 stars out to $\sim$20 parsecs.</td>
<td>$\geq$ 8 meter aperture</td>
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<tr>
<td></td>
<td>Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets</td>
<td>High contrast ($\Delta$Mag $&gt;$ 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA $\sim$ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times &lt;500 ksec</td>
<td>Stable $10^{-10}$ starlight suppression</td>
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<td></td>
<td></td>
<td></td>
<td>$\sim$0.1 nm stable WFE per 2 hr</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$\sim$1.3 to 1.6 mas pointing stability</td>
</tr>
<tr>
<td>What are star formation histories of galaxies?</td>
<td>Determine ages ($\sim$1 Gyr) and metallicities ($\sim$0.2 dex) of stellar populations over a broad range of galactic environments.</td>
<td>Color-magnitude diagrams of solar analog stars (Vmag$\sim$35 at 10 Mpc) in spiral, lenticular &amp; elliptical galaxies using broadband imaging</td>
<td>$\geq$ 8 meter aperture</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Symmetric PSF</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>500 nm diffraction limit</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.3 to 1.6 mas pointing stability</td>
</tr>
<tr>
<td>What are kinematic properties of Dark Matter</td>
<td>Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies</td>
<td>0.1 mas resolution for proper motion of $\sim$200 stars per galaxy accurate to $\sim$20 $\mu$as/yr at 50 kpc</td>
<td>$\geq$ 4 meter aperture</td>
</tr>
<tr>
<td>How do galaxies &amp; IGM interact and affect galaxy evolution?</td>
<td>Map properties &amp; kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to $\sim$10 Mpc.</td>
<td>SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in &lt; 2 weeks</td>
<td>500 nm diffraction limit</td>
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<tr>
<td></td>
<td>Measure UV Ly-alpha absorption due to Hydrogen “walls” from our heliosphere and atmospheres of nearby stars</td>
<td>High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars</td>
<td>Sensitivity down to 100 nm wavelength.</td>
</tr>
<tr>
<td>How do stars &amp; planets interact with interstellar medium?</td>
<td>UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth</td>
<td>SNR = 20 - 50 at spectral resolution of R $\sim$10,000 in FUV for 20 AB mag</td>
<td></td>
</tr>
</tbody>
</table>
Technology Challenges are derived directly from Science & Mission Requirements, and Implementation Constraints

<table>
<thead>
<tr>
<th>Science</th>
<th>Mission</th>
<th>Constraint</th>
<th>Capability</th>
<th>Technology Challenge</th>
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</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>EELV</td>
<td>5 m Fairing, 6.5 mt to SEL2</td>
<td>4 m Monolith</td>
<td>4 m, 200 Hz, 60 kg/m²</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>4 m support system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 m Monolith</td>
<td>2 m, 200 Hz, 15 kg/m²</td>
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<td></td>
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<td></td>
<td>8 m deployed support</td>
</tr>
<tr>
<td></td>
<td>HLLV-Medium</td>
<td>10 m Fairing, 40 mt to SEL2</td>
<td>8 m Monolith</td>
<td>8 m, &lt;100Hz, 200kg/m²</td>
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<tr>
<td></td>
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<td>8 m, 10 mt support</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>16 m Segmented</td>
<td>2-4m, 200Hz, 50kg/m²</td>
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<td>16 m deployed support</td>
</tr>
<tr>
<td></td>
<td>HLLV-Heavy</td>
<td>10 m Fairing, 60 mt to SEL2</td>
<td>8 m Monolith</td>
<td>8m, &lt;100Hz, 480kg/m²</td>
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<tr>
<td></td>
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<td>8 m, 20 mt support</td>
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<td></td>
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<td></td>
<td>16 m Segmented</td>
<td>2-4m, 200Hz, 120kg/m²</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>16 m deployed support</td>
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<tr>
<td>2 hr Exposure</td>
<td>Thermal</td>
<td>280K ± 0.5K, 0.1K per 10min</td>
<td>&lt; 5 nm rms per K</td>
<td>low CTE material</td>
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<tr>
<td></td>
<td>Dynamics</td>
<td>TBD micro-g</td>
<td>&gt; 20 hr thermal time constant</td>
<td>thermal mass</td>
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<tr>
<td></td>
<td>Reflectance</td>
<td>Substrate Size</td>
<td>&lt; 5 nm rms figure</td>
<td>passive isolation</td>
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<td></td>
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<td></td>
<td></td>
<td>active isolation</td>
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<tr>
<td>High Contrast</td>
<td>Monolithic</td>
<td>&lt; 10 nm rms figure</td>
<td>mid/high spatial error</td>
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<td></td>
<td>fabrication &amp; test</td>
<td></td>
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<tr>
<td></td>
<td>Segmented</td>
<td>&lt; 5 nm rms figure</td>
<td>edge fabrication &amp; test</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>&lt; 2 mm edges</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>passive edge constraint</td>
<td></td>
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<td></td>
<td>active align &amp; control</td>
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<td></td>
<td></td>
<td></td>
<td>&lt; 1 nm rms phasing</td>
<td></td>
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Telescope Performance Requirements

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 3 cases:

- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.
8m Telescope Requirements for Coronagraph

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Specification</th>
<th>Source</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Maximum total system rms WFE</td>
<td>38 nm</td>
<td>Diffraction limit (80% Strehl ratio at 500 nm)</td>
<td></td>
</tr>
<tr>
<td>Encircled Energy Fraction (EEF)</td>
<td>80% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture and slightly bluer wavelength</td>
<td>Vary &lt; 5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF stability</td>
<td>&lt;2%</td>
<td>JWST</td>
<td></td>
</tr>
<tr>
<td>WFE stability over 20 minutes</td>
<td>~1.5 nm</td>
<td>λ/500 at 760 nm</td>
<td></td>
</tr>
<tr>
<td>PM rms surface error</td>
<td>5 - 10 nm</td>
<td>HST / ATLAST studies</td>
<td></td>
</tr>
<tr>
<td>Pointing stability (jitter)</td>
<td>~2 mas</td>
<td>Guyon, scaled from HST</td>
<td>~ 0.5 mas floor determined by stellar angular diameter.</td>
</tr>
<tr>
<td>Mid-frequency WFE</td>
<td>&lt; 20 nm</td>
<td>HST</td>
<td></td>
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Primary Mirror Total Surface Figure Requirement

Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:

- **Observatory**: 40 nm rms
  - **Instruments**: 15 nm rms
  - **Telescope**: 36 nm rms
  - **Pointing Control**: 10 nm rms

The flowing the Telescope Level Requirements to its major Sub-Systems:

- **Telescope**: 36 nm rms
  - **PMA**: 20 nm rms
  - **SMA**: 16 nm rms
  - **Stability**: 20 nm rms
  - **Assemble, Align**: 16 nm rms
Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or phased, PM must have < 10 nm rms surface.

Monolithic PM Specification depends on its Thermal behavior and Mounting Uncertainty, leaving < ~ 8 nm rms for Total Manufactured WFE.

Segmenting increases complexity and redistributes the error allocations. But there is currently no consensus on the Segment Phasing error allocation.
Future large aperture space telescopes need low-areal-density high-stiffness mirror substrates. This requires deeper substrates.

State of the Art is ATT Mirror: 2.4 m, 3-layer, 0.3 m deep, 60 kg/m² substrate
Also 1.4 m AMSD and 1 m Kepler
43 cm Deep Core Mirror

Exelis successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m² mirror substrate.

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Mid/High Spatial Frequency

UVOIR telescopes require a ~ 7 nm rms primary mirror surface figure.

State of the Art for 60 kg/m² mirrors is:
- ~ 10 nm rms on AMSD
- ~ 20 nm rms on ATT

HST at 170 kg/m² mirrors was ~ 7 nm rms.
Mid/High Spatial Frequency Error

Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.

Capability is traceable to UVOIR figure specification.

MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)


Model Validation

On-orbit performance is determined by mechanical and thermal stability. Future systems require validated performance models.
Deep Core Thermal Model

Thermal Model of 43 cm deep core mirror generated and validate by test.

43 cm deep core mirror tested from 250 to 300K

Test Instrumentation

- 4D Instantaneous Interferometer to measure surface Wavefront Error
- InSb Micro-bolometer to measure front surface temperature gradient to 0.05C
- 12 Thermal Diodes.

NOTE: This was first ever XRCF test using thermal imaging to monitor temperature


Edge Apodization

Successfully demonstrated achromatic edge apodization process.

This technology minimizes segment edge diffraction and straylight on high-contrast imaging PSF.

Primary mirror segment gap apodization in the optical

A. Sivaramakrishnan, G. L. Carr, R. Smith, X. X. Xi, & N. T. Zimmerman

Apodization mitigates segment gaps
Achromatic apodization in collimated space
Tolerancing can be tight
Gemini Planet Imager (1.1-2.4 um) – 0.5% accuracy req.
UVOIR space coronagraph - 0.55 – 1.1 um
Metal-on-glass dots look OK
Next
Develop & confirm on reflective surfaces
Reqs. on accuracy, reflectivity, absorption/, polarization?
Use larger dots to reduce non-linearity

40 test transmissions written with 5 um
Al on Cr microdots on Infrasil glass

Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.
Design Tools and Point Designs
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

*Point Designs:* AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.

![Free-Free 1st Mode: 4 m dia 40 cm thick substrate](image1)

![Internal Stress: 4 m dia with 6 support pads](image2)

*Support System:* AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.


Monolithic Substrate Point Designs

4-m designs are mass constrained to 720 kg for launch on EELV

8-m designs are mass constrained to 22 mt for launch on SLS
Trade Study Concept #1: 4 m Solid

Design:
- Diameter: 4 meters
- Thickness: 26.5 mm
- Mass: 716 kg
- First Mode: 9.8 Hz
Trade Study Concept #2: 4 meter Lightweight

Design:
- Diameter: 4 meters
- Thickness: 410 mm
- Facesheet: 3 mm
- Mass: 621 kg
- First Mode: 124.5 Hz
Trade Study Concept #3: 8 meter Solid 22 MT

Design:
- Diameter: 8 meter
- Thickness: 200 mm
- Mass: 21,800 kg
- First Mode: 18 Hz

Same as ATLAST Study

<table>
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<tr>
<th>SET</th>
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<tr>
<td>1</td>
<td>18.026</td>
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<td>74.041</td>
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<td>74.045</td>
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<td>8</td>
<td>75.174</td>
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<tr>
<td>9</td>
<td>75.176</td>
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<tr>
<td>10</td>
<td>112.96</td>
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</tbody>
</table>
Trade Study Concept #4: 8 meter Lightweight

Design:
- Diameter: 8 meter
- Thickness: 510 mm
- Facesheet: 7 mm
- Mass: 3,640 kg
- First Mode: 48.4 Hz
Modeling Tool
Program Control Window
Isogrid and Simplified Meshes
Easily Add a Central Hole
Segmented Mirrors
Almost Unlimited Size
Circular Segmented Mirrors
Model can be Merged in One Mirror
Whole Mirror or Segment Supports
Radial Support
Axial Support
Generate Static Loading Conditions
Generate Dynamic Loading Sets
ULE CTE Mapping
Conclusions

Assembled outstanding team from academia, industry and government with expertise in science and space telescope engineering.

Derived engineering specifications for monolithic primary mirror from science measurement needs & implementation constraints.

Pursuing long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Successfully demonstrated capability to make 0.5 m deep mirror substrate and polish it to UVOIR traceable figure specification.